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ESTIMATION OF CONTROL FORCES OF SPRING-TAB AILERONS FROM WIND-TUNNEL DATA

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SUMMARY

A method is presented for estimating the control forces of spring-tab ailerons from nonlinear wind-tunnel data. The method applies to the most general form of spring-tab system, the geared spring tab. The two principal arrangements of the ailerons and spring unit are considered. These arrangements are (1) an arrangement wherein the ailerons are interconnected and employ a central spring unit and (2) an arrangement with no interconnection between the ailerons with individual preloaded spring units for each aileron. Static wind-tunnel data consisting of both aileron and tab hinge-moment coefficients are required as well as the characteristics of the linkage system.

The effects of the rolling motion of the airplane on the control forces and wing-tip helix angles are accounted for by the procedure given in NACA ARR No. L5F23. An empirical correction is employed to account for the effects of yaw, yawing motion, and wing twist on the wing-tip helix angle of the airplane. An example is given to illustrate briefly the computations involved in the method.

INTRODUCTION

The application of spring tabs to ailerons has the advantage of reducing the difference between the control forces at high and low speeds for a stated value of wing-tip helix angle. For aileron controls an initial hinge moment will usually exist at neutral aileron deflection. These hinge moments result from the variation of the aileron and tab hinge moments with angle of attack and may become quite large at high angles of attack. When spring tabs are employed this initial hinge moment will tend to cause both ailerons to deflect in the same direction (against the spring unit) until the aileron hinge moments are balanced by the moment contributed by the spring unit and the tabs. Two principal arrangements of the aileron and spring unit can be used to prevent the ailerons from deflecting excessively as a result of these hinge moments - (1) an arrangement wherein the ailerons are interconnected and employ a central spring unit and (2) an arrangement wherein the ailerons are not interconnected and employ individual preloaded spring units for each aileron. In the first arrangement the interconnection between the ailerons prevents them from deflecting in the same direction, whereas in the second arrangement the preload of the spring units prevents the aileron from deflecting excessively.

Existing methods for estimating control forces of spring-tab controls (for example, reference 1) assume linear variations of aileron and tab hinge-moment coefficients with control deflection, tab deflection, and angle of attack. This assumption is generally justified for controls, the deflections of which do not exceed the range of deflection for which the hinge-moment characteristics are linear. For controls which require large deflections, such methods are not applicable.

The method presented herein was therefore developed for estimating the control forces for spring-tab ailerons from nonlinear wind-tunnel data. The basic principles of the method, however, can be applied in the estimation of the forces of other controls. The method includes both arrangements of the aileron and spring unit. A brief discussion of the changes in the method for a differential linkage is also presented. An example is included to illustrate briefly the computations involved in the method used when the ailerons are interconnected.

SYMBOLS

C_L lift coefficient

c_l section lift coefficient

C_l rolling-moment coefficient

C_{h_a} aileron hinge-moment coefficient

C_{h_t} tab hinge-moment coefficient

a_o rate of change of section lift coefficient with angle of attack $(dc_l/d\alpha_o)$

C_{l_p} rate of change of rolling-moment coefficient with wing-tip helix angle $\left(\dfrac{\partial C_l}{\partial(pb/2V)}\right)$

$pb/2V$	wing-tip helix angle, radians
α_o	section angle of attack, degrees
α	wing angle of attack, degrees
ΔC_l	increment in rolling-moment coefficient due to deflection of both ailerons
$(\Delta\alpha)_p$	increment of angle of attack due to rolling
B_1	factor employed in evaluating $(\Delta\alpha)_p$
δ_c	control wheel deflection, degrees
δ_a	aileron deflection, positive when aileron is moved down, degrees
δ_t	tab deflection, positive when tab is moved down, degrees
δ_h	aileron horn deflection, opposite in sign to aileron deflection when both are deflected in same direction, degrees
θ	total difference between horn and aileron deflections $(\theta' + \Delta\theta)$ positive when producing a more positive tab deflection
θ'	$\left(\frac{1 - l}{m}\right)\delta_a$
$\Delta\theta$	difference between aileron and horn deflections due to deflection of spring unit, positive when producing a more positive tab deflection
H_a	aileron hinge moment, positive when tending to produce a more positive aileron deflection, foot-pounds
H_t	tab hinge moment, positive when tending to produce a more positive tab deflection, foot-pounds
F_T	total force in link R (see fig. 1(a)), positive when opposing deflection of ailerons, pounds
F_c	control force tangent to control wheel, pounds
F_T'	total force in link Q, positive when opposing the deflection of the ailerons, pounds

F_a	force at end of aileron horn contributed by each tab, positive when opposing deflection of ailerons, pounds
F_b	force required to deflect spring, positive when opposing deflection of ailerons, pounds
K	spring-unit constant, foot-pounds per degree $\Delta\theta$
R	linkage ratio (m/n)
V	airspeed, feet per second
V_i	indicated airspeed, miles per hour
p	angular velocity in roll, radians per second
q	dynamic pressure, pounds per square foot
b	wing span, feet
b_a	aileron span, feet
b_t	tab span, feet
$\bar{c}_a$	aileron root-mean-square chord, feet
$\bar{c}_t$	tab root-mean-square chord, feet
λ	taper ratio (ratio of tip chord to root chord)
r	radius of control wheel
P	spring unit preload, foot-pounds
l, m, n	dimensions of spring-tab system (see fig. 1)

Constants

$$C_1 = \frac{0.8}{C_{l_p}}$$

$$C_2 = \frac{(\Delta\alpha)_p}{B_1\left(\frac{pb}{2V}\right)} \frac{B_1}{C_{l_p}}$$

$$C_3 = q b_a \bar{c}_a^{\,2}$$

$C_4 = Rqb_t\bar{c}_t^2$

$C_5 = \frac{1}{r}\frac{d\delta_h}{d\delta_c}$

METHOD OF CALCULATION

Spring-tab control systems may be divided into two general classifications, the ordinary or ungeared spring-tab system and the geared spring-tab system. In the ordinary spring-tab system when the control wheel is deflected with the system under no load the tab does not deflect, whereas in the geared spring-tab system the tab deflects. The two principal configurations of aileron spring tabs (ailerons interconnected and not interconnected) are shown in figure 1. From this diagram it is evident that the ordinary spring-tab system is a special case of the geared spring-tab system. When the dimensions l and m (fig. 1) are equal the system has no gearing, when $l > m$ the tab is geared in the conventional manner and when $l < m$ the tab will lead the aileron.

Assumptions

The basic assumptions involved in the procedures are as follows:

(1) The rolling motion of the airplane is steady

(2) The effects of aileron and horn deflections on the linkages are negligible

(3) The effects of wing deflection and friction on the control forces are negligible

Assumption (1) is justified inasmuch as the effect of variations in the rolling velocity on the aileron control forces are very small. For assumption (2) the changes in the linkages for various aileron and horn deflections are small and the resultant effect on the aileron control forces has been neglected. The effect of friction noted in assumption (3) is not negligible but no general procedure exists to account for this effect, which depends upon the linkage arrangement and condition of the control system involved. Similarly, no general procedure exists to account for the effect of wing deflection, which depends upon the rigidity of the wing involved.

Effect of the Airplane Rolling Motion

In the calculation of both the control force and wing-tip helix angle from static wind-tunnel data the steady rolling motion of the airplane must be considered. The effect of rolling motion on the rolling-moment and hinge-moment characteristics is described in references 2 and 3; however, the basic parameters which are required to determine the effect of rolling are presented herein with a brief description of the procedure.

The rolling effect on the aerodynamic characteristics of the aileron and tab results from the increase in angle of attack over the downgoing wing and the decrease in angle of attack over the upgoing wing. The magnitude of the angle-of-attack change varies approximately linearly over the wing semispan; however, the net effect of the rolling motion can be represented by a constant increment in angle of attack, which is obtained from figure 2.

The value of the wing-tip helix angle $pb/2V$ is determined from the relationship

$$\frac{pb}{2V} = 0.8\,\frac{\Delta C_l}{C_{l_p}} \tag{1}$$

The value of the parameter C_{l_p} for various wing plan forms is presented in figure 3. The constant 0.8 is employed in equation (1) to estimate the value of $pb/2V$ for the airplane. The constant 0.8 is an empirical factor intended to account for the effect of yaw and yawing-motion at low speeds and wing twist at high speeds and should not be used in the determination of $(\Delta\alpha)_p$.

Case I - Ailerons Interconnected, Central Spring Unit

The arrangement of the aileron, tab, and spring unit are shown in figure 1(a). It is evident from this figure that the deflection of each aileron and control horn will be equal in magnitude but opposite in sign. The tab deflections will not necessarily be equal but will be determined as a function of θ from the particular arrangement of the aileron, horn, and tab. The exact relation between δ_t and θ has been worked out and for very small values of θ the following equation closely approximates this exact relation:

$$\delta_t = R\,\theta \tag{2}$$

From figure 1(a) it is evident that

$$F_T = F_{a_{-\delta_a}} + F_{a_{\delta_a}} + F_b \tag{3}$$

and

$$F_T l = \left(F_{a_{-\delta_a}} + F_{a_{\delta_a}}\right) l + F_b l \tag{4}$$

The subscripts δ_a and $-\delta_a$ refer herein to the positively and negatively deflected ailerons. When the ailerons are in equilibrium

$$\left(F_{a_{-\delta_a}} + F_{a_{\delta_a}}\right) m + F_b l = H_{a_{-\delta_a}} - H_{a_{\delta_a}} \tag{5}$$

Similarly, when the tabs are in equilibrium

$$\left(F_{a_{-\delta_a}} + F_{a_{\delta_a}}\right) n = H_{t_{\delta_a}} - H_{t_{-\delta_a}} \tag{6}$$

Introducing equation (6) into equation (5) gives

$$F_b l = H_{a_{-\delta_a}} - H_{a_{\delta_a}} - \frac{m}{n}\left(H_{t_{\delta_a}} - H_{t_{-\delta_a}}\right) \tag{7}$$

and

$$K = \frac{1}{|\Delta\theta|}\left[H_{a_{-\delta_a}} - H_{a_{\delta_a}} - \frac{m}{n}\left(H_{t_{\delta_a}} - H_{t_{-\delta_a}}\right)\right] \tag{8}$$

From equation (8) the spring-unit constant which would be required for equilibrium of the system for given deflections of the aileron and horn can be determined. In the solution of equation (8) the aileron and tab hinge moments are corrected for the effect of the rolling motion and the value of K applies to the particular angle of attack of the airplane as it enters the rolling maneuver. If the values of K are plotted against corresponding values of $|\Delta\theta|$, the horn and tab deflections at which the system will be in equilibrium can be determined for any value of the spring-unit constant at the various aileron deflections.

Combining equations (3) and (5) gives the expression for the moment of the force F_T about the aileron hinge

$$F_T m = H_{a_{-\delta_a}} - H_{a_{\delta_a}} + F_b(m - l) \tag{9}$$

or

$$F_T m = H_{a_{-\delta_a}} - H_{a_{\delta_a}} + K\left|\Delta\theta\right|\left(\frac{m}{l} - 1\right) \tag{10}$$

The aileron control force is then determined from the following equation:

$$F_c = \frac{F_T m}{r}\frac{d\delta_h}{d\delta_c} \tag{11}$$

For values of $\Delta\theta$ equal to zero, a positive value for the term in brackets of equation (8) indicates that the aileron is underbalanced and a negative value indicates that the aileron is overbalanced. When the aileron is overbalanced (as could result from some form of additional aerodynamic balance) the conventional tab gearing can be reversed (causing the tab to lead the aileron) to correct the overbalance. For the tab-leading condition the ratio l/m will be less than unity. When any aileron overbalance is not corrected by means of the tab gearing, the value of K will be negative for those aileron deflections for which the aileron is overbalanced.

As the assumed values of $\Delta\theta$ are increased the value of K may change sign. A change in sign from positive to negative indicates that the aileron was initially underbalanced (tab neutral) and has become overbalanced as a result of assuming too large a value for $\Delta\theta$ at that aileron deflection under consideration. Conversely, a change in sign from negative to positive indicates that the aileron was initially overbalanced as a result of some additional aerodynamic balance (and not corrected by tab gearing) and has become underbalanced as a result of assuming too large a value for $\Delta\theta$. Inasmuch as a spring-tab system will not become overbalanced as a result of excessive deflection of the spring, the conditions represented by the change in the sign of K could not occur. Therefore, when the system is initially underbalanced only positive values of K are considered, and when the system is overbalanced (and not corrected by tab gearing) only negative values of K are considered.

When a differential linkage is employed the aileron and horn deflections will not be equal for a given deflection of the control wheel and consequently the value of $\Delta\theta$ will be different for each aileron. The spring-unit constant will then be defined in terms of the value of $\Delta\theta$ for one of the ailerons. In the determination of the control force the mechanical advantage $d\delta_h/d\delta_c$ will be different for each aileron. Combining equations (3), (5), (8), and (11) in a slightly different manner gives an expression for the control force for a system employing a differential linkage:

$$F_c = \frac{1}{r}\left[\frac{m}{l}H_{a_{-\delta_a}} + \frac{m}{n}\left(\frac{m}{l} - 1\right)H_{t_{-\delta_a}}\right]\left(\frac{d\delta_h}{d\delta_c}\right)_{-\delta_a} - \frac{1}{r}\left[\frac{m}{l}H_{a_{\delta_a}} + \frac{m}{n}\left(\frac{m}{l} - 1\right)H_{t_{\delta_a}}\right]\left(\frac{d\delta_h}{d\delta_c}\right)_{\delta_a}$$

Case II - Ailerons Not Interconnected,

Separate Spring Units

The arrangement of the aileron, tab, and spring unit are shown in figure 1(b). In this arrangement only the aileron horn deflections will be equal (assuming no differential linkage); the aileron and tab deflections will not necessarily be equal. As in case I the tab deflections are determined from the particular arrangement of the aileron and horn.

As previously noted, the spring unit must be preloaded an amount sufficient to prevent the ailerons from deflecting excessively in the same direction as a result of the initial hinge moments of the aileron and tab at $\delta_a = 0$. If it is not objectionable for the ailerons to float up slightly in some attitudes the amount of preload may be adjusted accordingly.

The equations for this configuration are similar to those for case I. Inasmuch as the action of each aileron is independent of the other, the conditions for equilibrium must be determined for each aileron individually. From figure 1(b) it is evident that for each aileron

$$F_T' = F_a + F_b \qquad (12)$$

and

$$F_T'l = F_al + F_bl \qquad (13)$$

When the aileron is in equilibrium

$$F_a m + F_b l = H_a \tag{14}$$

Similarly, when the tabs are in equilibrium

$$F_a n = -H_t \tag{15}$$

Introducing equation (15) into equation (14) gives

$$F_b l = H_a + \frac{m}{n} H_t \tag{16}$$

and

$$K = \frac{1}{\Delta\theta}\left(H_a + \frac{m}{n} H_t\right) \tag{17}$$

Since the spring-unit constant will be equal for each aileron

$$\frac{H_{a_{\delta_a}} + \frac{m}{n} H_{t_{\delta_a}}}{\Delta\theta_{\delta_a}} = K = \frac{H_{a_{-\delta_a}} + \frac{m}{n} H_{t_{-\delta_a}}}{\Delta\theta_{-\delta_a}} \tag{18}$$

Introducing the value of the spring-unit preload into equation (18)

$$\frac{H_{a_{\delta_a}} + \frac{m}{n} H_{t_{\delta_a}} - P}{\Delta\theta_{\delta_a}} = K = \frac{H_{a_{-\delta_a}} + \frac{m}{n} H_{t_{-\delta_a}} - P}{\Delta\theta_{-\delta_a}} \tag{19}$$

It should be noted that equation (19) may be applied only when $\left|H_a + \frac{m}{n} H_t\right|$ for each aileron exceeds the magnitude of the spring-unit preload P. If the preload is not exceeded $\Delta\theta$ will be zero and the system will be equivalent to one in which the spring-unit constant is infinite. The solution of equation (19) (with the exception of special cases) is accomplished by means of successive approximations. For a given value of δ_h the value of $\Delta\theta$ is assumed and the right and left sides of equation (19) must be equal for equilibrium of the system. If the calculated value of K does not equal the value corresponding to the chosen spring, a second assumption for the value of $\Delta\theta$ is made and the procedure is repeated.

The control force is determined from the moment of the total force F_T' about the aileron hinge. Combining equations (12) and (14) gives

$$F_T'm = H_a + F_b(m - l)$$

or

$$F_T'm = H_a + K\,\Delta\theta\left(\frac{m}{l} - 1\right) \tag{20}$$

The control force is then determined from the moment of the force F_T' for both ailerons in the same manner as that for case I.

When the spring-unit preload is small the ailerons will deflect to an angle which is determined by the speed, the initial angle of attack of the airplane, and the value of the spring-unit constant. The aileron angle is determined by equation (19) in which the value of $\Delta\theta$ will be equal to the aileron angle. The computation of the control forces is accomplished in the manner previously described.

It should be noted that the hinge moment of the aileron on the downgoing wing will decrease as the control wheel is deflected. If the preload is comparatively large (but not sufficient to prevent the ailerons from deflecting), the magnitude of the term $\left|H_a + \frac{m}{n} H_t\right|$ of equation (19) may become less than the spring-unit preload; thus, the tab deflection is reduced to zero for the aileron of the downgoing wing. When such a condition exists the value of $\Delta\theta$ for that aileron will be zero and its deflection will be equal to the horn deflection. Thus, it is possible to use a direct procedure analogous to that for case I for those aileron deflections when this condition exists.

ILLUSTRATIVE EXAMPLE

In order to illustrate briefly the computation procedure an example is presented. The example illustrates the computations for case I where the ailerons are interconnected. For case II (no interconnection between the ailerons) the computations are similar and tables can be arranged to facilitate the computations. The wind-tunnel data were obtained from tests of a partial-span model of a bomber-type airplane.

Geometric Characteristics and Conditions of the Assumed Airplane

The geometric characteristics of the airplane and the data required for the computations are as follows:

Wing span, b, feet	230
Aspect ratio	11.1
Wing loading, pounds per square foot	57
Taper ratio, λ	0.25
Ailerons:	
chord, percent c	20
internal sealed balance, percent c_a	54
Inboard end of aileron, percent $b/2$	59
Outboard end of aileron, percent $b/2$	99
$b_a\bar{c}_a^2$, cubic feet	352
$b_t\bar{c}_t^2$, cubic feet	7.81
$\frac{d\delta_h}{d\delta_c}$	0.20
Control-wheel radius, r, feet	0.583
R	2.5
l/m	2/3
Spring-unit constant, K, foot-pounds per degree	50

The wind-tunnel test results are usually obtained in the form presented in figure 4. In order to account for the effect of the rolling motion of the airplane, cross plots (fig. 5) are made in which the data of figure 4 are plotted against angle of attack. Cross plots are usually made for 4 or 5 aileron deflections.

The conditions selected for the example are representative of the landing configuration of the airplane, with flaps deflected and $\alpha = 14.0^\circ$, $C_L = 1.9$, $V_i = 108$, and $q = 30$. The constants required for the computations of the wing-tip helix angle and the correction to the angle of attack for the effect of rolling are determined from figures 2 and 3 as follows:

$$\frac{C_{l_p}}{a_o} = 4.67$$

$$\frac{(\Delta\alpha)_p}{B_1\left(\frac{pb}{2V}\right)} = -42.5$$

$$B_1 = 0.85$$

The value of a_o was obtained from two-dimensional tests to be 0.114 and consequently

$$C_{l_p} = 0.532$$

These constants are combined in several arrangements, which are used frequently in the computations, as follows:

$$C_1 = 1.50$$

$$C_2 = -67.9$$

$$C_3 = 10,560$$

$$C_4 = 586$$

$$C_5 = 0.343$$

Computation Procedure

Table I.- In table I the first four columns are determined from the relationship between δ_a, θ', and $\Delta\theta$. The values of $\Delta\theta$ are arbitrary. The computation procedure is outlined as follows:

Columns (5) and (6): The value of each tab deflection will depend upon the relationship between θ and δ_t and for this example is

$$\delta_t = 2.5\theta$$

Column (7): The total increment in rolling-moment coefficient is determined from figure 6 for each tab deflection at $\alpha = 14.0^{\circ}$. The total increment in rolling-moment coefficient is

$$\Delta C_l = C_{l_{\delta_a}} - C_{l_{-\delta_a}}$$

Column (8): The increment in angle of attack used to account for the effect of rolling is obtained by multiplying column (7) by constant C_2. Inasmuch as the values of ΔC_l have not been corrected for the effect of rolling these increments in angle of attack represent only a first approximation; however, since the values of $(\Delta\alpha)_p$ are calculated to one decimal placo no error is introduced by employing only a first approximation.

Columns (9) and (10): The increment in angle of attack is added to the wing angle of attack (14.0°) for the positive aileron deflection (column (9)) and subtracted for the negative aileron deflection (column (10)).

Columns (11) and (12): The aileron hinge-moment coefficients are obtained at the propor angle of attack and tab deflection from figure 5.

Columns (13) and (14): The tab hinge-moment coefficients are obtained at the proper angle of attack and tab deflection from figure 5. It should be noted that the same increment in angle of attack is employed to account for the rolling effoct on the tab hinge-moment coefficients as that for the aileron hinge-moment coefficients but, since the magnitude of the tab hinge moment is small compared to the aileron hinge moment, any error introduced by employing the same angle of attack for the tab as that used for the aileron would be negligible.

Columns (15) and (16): The aileron hinge moments are obtained by multiplying columns (11) and (12) (aileron hinge-moment coefficients) by constant C_3.

Columns (17) and (18): The effective tab hinge moments are obtained by multiplying columns (13) and (14) by constant C_4.

Column (19): The hinge moment contributed by tho spring unit is obtained by use of the relationship given by equation (7),

$$H_{a_{-\delta_a}} - H_{a_{\delta_a}} + RH_{t_{-\delta_a}} - RH_{t_{\delta_a}}$$

Column (20): The spring-unit constant is determined by dividing the hinge moment contributed by the spring by the magnitude of $\Delta\theta$. Inasmuch as $\Delta\theta$ has both a positive and a negative sign (depending on the aileron deflection) only the magnitude is considered. The value of the spring-unit constant is that which would be required for equilibrium of the system for that particular aileron deflection and $\Delta\theta$.

A plot of the values of the spring-unit constant for the various values of $\Delta\theta$ is presented in figure 6. From this figure the value of $\Delta\theta$ required for equilibrium of the system (for the initial angle of attack) can be determined for each aileron deflection at any value of the spring constant. The control force is then determined by the aileron hinge moment at each equilibrium condition.

Table II.- For a given value of the spring-unit constant the control forces and corresponding values of the wing-tip helix angle are determined in table II. The value of the spring-unit constant for the example was chosen as 50 foot-pounds per degree. The computations of the control force and wing-tip helix angle are outlined according to the columns of the table as follows:

Columns (1) to (6): The value of $\Delta\theta$ at which the system will be in equilibrium for each aileron deflection is determined from figure 6. From the value of θ' and $\Delta\theta$ the value of θ and the corresponding tab deflections are determined as in table I.

Column (7): The total increment in rolling-moment coefficient is determined as in column (7) of table I for the particular tab deflections.

Columns (8) to (10): The increment in angle of attack and the angles of attack for each aileron deflection are determined in the same manner as in columns (8) to (10) of table I.

Column (11): The total increment in rolling-moment coefficient is determined at the proper angle of attack for the positive and negative deflection of the aileron. If the values of columns (7) and (11) are equal, the rolling motion of the airplane has no effect on the rolling-moment coefficients. If, however, the values of columns (7) and (11) are not equal a second approximation must be made in which the value of column (7) is taken as the preceding value in column (11) and the procedure repeated until the values of columns (7) and (11) are equal. In general, two approximations will be sufficient.

Column (12): The wing-tip helix angles are obtained by multiplying the final values of column (11) by the constant C_1.

Columns (13) and (14): The aileron hinge-moment coefficients are determined at the corrected angles of attack (which determinod the final value of rolling-moment coefficient) from figure 5.

Column (15): The net aileron hinge moment is obtained as $C_3\left(C_{h_{a_{-\delta_a}}} - C_{h_{a_{\delta_a}}}\right)$.

Column (16): In obtaining the product $K|\Delta\theta|\left(\frac{m}{l}-1\right)$, the spring unit constant for this example is 50 foot-pounds per degree and the constant $\frac{m}{l}-1$ is 0.5.

Column (17): The control force is determined by multiplying the sum of columns (15) and (16) by C_5.

CONCLUDING REMARKS

A method is presented for estimating the control forces of spring-tab ailerons from wind-tunnel data. The method applies to the most general form of spring-tab system, the geared spring tab. The two principal arrangements of the aileron and spring unit are considered and an example of the computation is presented. The rolling effect on the control forces and rates of roll are included in the computations and approximate corrections for the effect of yaw, yawing motion, and wing twist on the rates of roll are made.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
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TABLE I

CALCULATION OF SPRING-UNIT CONSTANT

[α 14.0°; C_2 -67.9; C_3 10560; C_4 586]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
δ_a (deg)	θ' (deg)	$\Delta\theta$ (deg)	θ (deg)	$\delta_{t_{\delta_a}}$ (deg)	$\delta_{t_{-\delta_a}}$ (deg)	ΔC_l	$(\Delta\alpha)_p$ (deg)	α_{δ_a} (deg)	$\alpha_{-\delta_a}$ (deg)	$C_{h_{a_{\delta_a}}}$	$C_{h_{a_{-\delta_a}}}$	$C_{h_{t_{\delta_a}}}$	$C_{h_{t_{-\delta_a}}}$	$H_{a_{\delta_a}}$ (ft-lb)	$H_{a_{-\delta_a}}$ (ft-lb)	$RH_{t_{\delta_a}}$ (ft-lb)	$RH_{t_{-\delta_a}}$ (ft-lb)	$F_b l$ (ft-lb)	K (ft-lb/deg)
±12	±4	∓2.0	±2.0	5.0	-5.0	0.0294	-2.0	12.0	16.0	-0.1346	0.0074	-0.0887	0.0420	-1421	78	-52	25	1576	788
		∓3.0	±1.0	2.5	-2.5	.0275	-1.9	12.1	15.9	-.1310	-.0010	-.0799	.0340	-1383	-11	-47	20	1439	480
		∓4.0	0	0	0	.0256	-1.7	12.3	15.7	-.1285	-.0090	-.0712	.0260	-1357	-95	-42	15	1319	330
		∓5.0	∓1.0	-2.5	2.5	.0256	-1.7	12.3	15.7	-.1165	-.0140	-.0510	.0142	-1230	-148	-30	8	1120	224
		∓6.0	∓2.0	-5.0	5.0	.0255	-1.7	12.3	15.7	-.1050	-.0192	-.0320	.0027	-1109	-203	-19	2	927	155
		∓7.0	∓3.0	-7.5	7.5	.0245	-1.7	12.3	15.7	-.0980	-.0242	-.0180	-.0078	-1035	-256	-11	-5	785	112
		∓8.0	∓4.0	-10.0	10.0	.0234	-1.6	12.4	15.6	-.0916	-.0297	-.0044	-.0180	-967	-314	-3	-11	645	81
		∓10.0	∓6.0	-15.0	15.0	.0215	-1.5	12.5	15.5	-.0787	-.0426	.0210	-.0428	-831	-450	12	-25	344	34
		∓12.0	∓8.0	-20.0	20.0	.0194	-1.3	12.7	15.3	-.0650	-.0552	.0446	-.0806	-686	-583	26	-47	30	3

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TABLE II

CALCULATION OF CONTROL FORCES AND WING-TIP HELIX ANGLE

[K 50 ; α 14.0° ; C_1 1.50 ; C_2 -67.9 ; C_3 10,560 ; C_5 0.343]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
δ_a (deg)	θ' (deg)	$\Delta\theta$ (deg)	θ (deg)	$\delta_{t_{\delta_a}}$ (deg)	$\delta_{t_{-\delta_a}}$ (deg)	ΔC_l	$(\Delta\alpha)_p$ (deg)	α_{δ_a} (deg)	$\alpha_{-\delta_a}$ (deg)	ΔC_l	$\frac{pb}{2V}$ (radian)	$C_{h_{a_{\delta_a}}}$	$C_{h_{a_{-\delta_a}}}$	ΔH_a (ft-lb)	$K\lvert\Delta\theta\rvert\left(\frac{m}{2} - 1\right)$ (ft-lb)	F_o (lb)
±3	±1	∓2.3	∓1.3	-3.25	3.25	0.0056	-0.3	13.7	14.3	0.0056	0.0084	-0.0687	-0.0581	112	57.5	58
±6	±2	∓4.6	∓2.6	-6.50	6.50	.0111 .0112	-.6 -.6	13.4 13.4	14.6 14.6	.0112 .0112	.0168	-.0718	-.0479	252	115	126
±9	±3	∓7.0	∓4.0	-10.00	10.00	.0165 .0169	-.9 -.9	13.1 13.1	14.9 14.9	.0169 .0169	.0254	-.0770	-.0405	386	175	192
±12	±4	∓9.4	∓5.4	-13.50	13.50	.0220 .0224	-1.5 -1.5	12.5 12.5	15.5 15.5	.0224 .0224	.0336	-.0822	-.0380	467	235	241
±15	±5	∓12.1	∓7.1	-17.75	17.75	.0258 .0269 .0270	-1.4 -1.5 -1.5	12.6 12.5 12.5	15.4 15.5 15.5	.0269 .0270 .0270	.0405	-.0892	-.0323	601	303	310

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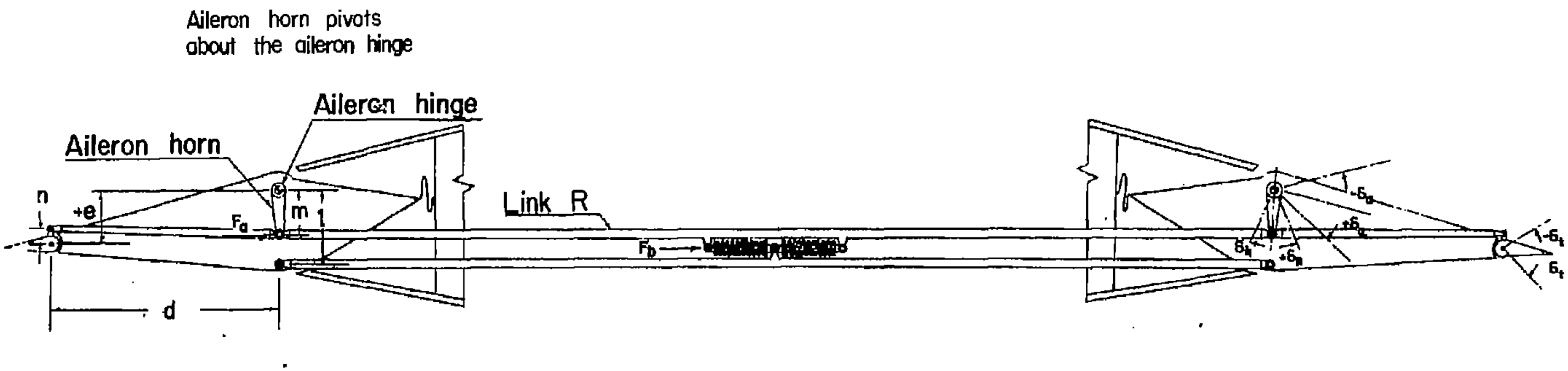
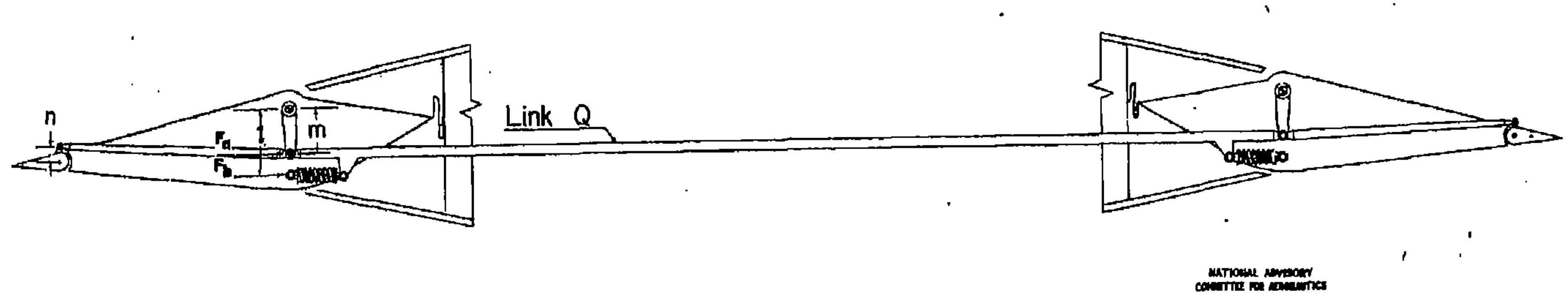


(a) Ailerons interconnected, central spring unit.



(b) Ailerons not interconnected, separate spring units.

Figure 1.- Schematic diagram of the two principal configurations of aileron spring-tab systems.

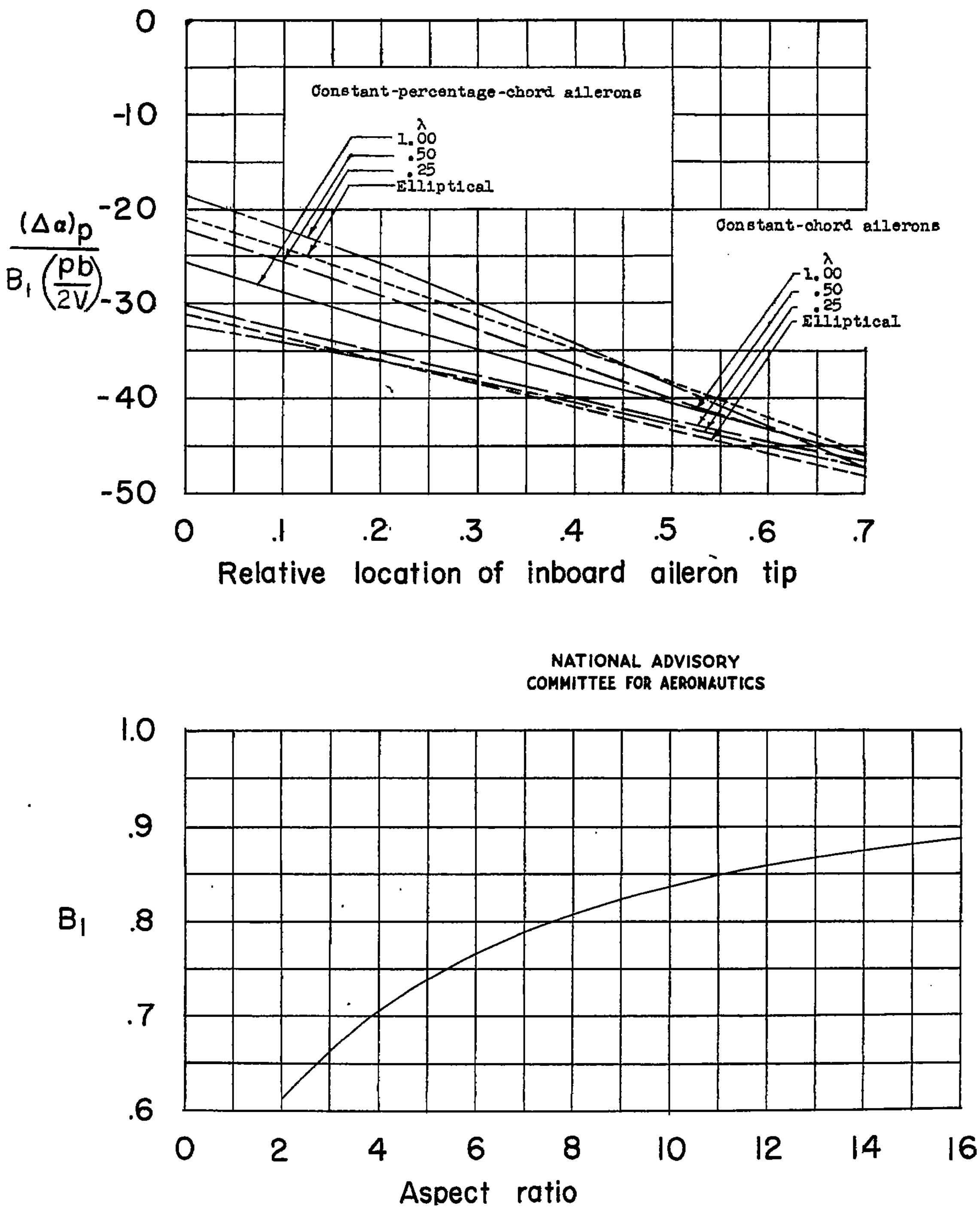


Figure 2.- Chart for determining the parameter used in the computation of the change in angle of attack at the aileron (from reference 3).

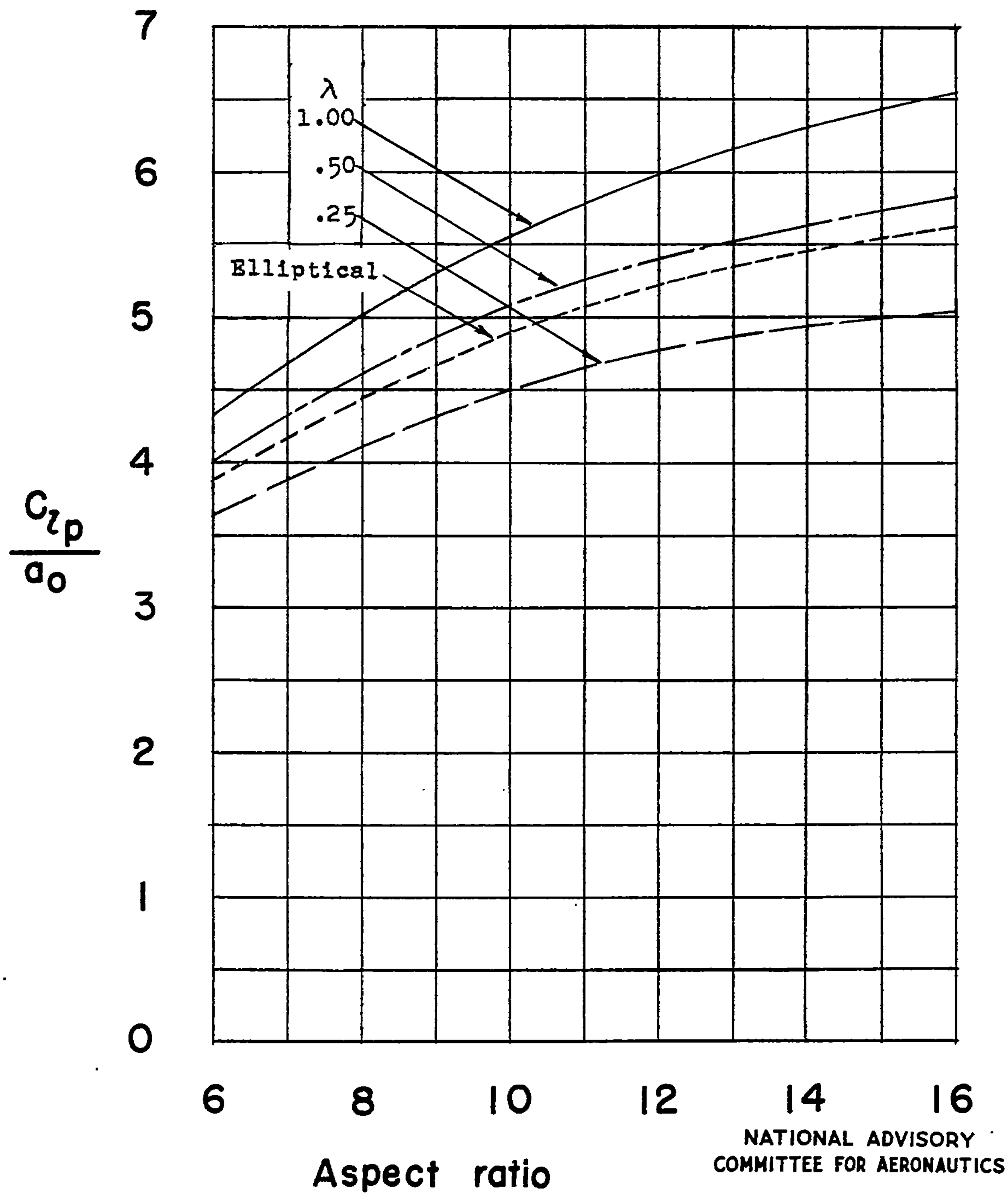


Figure 3.- The variation of the damping coefficient in terms of the slope of the section lift curve with aspect ratio for various values of the taper ratio (from reference 2).

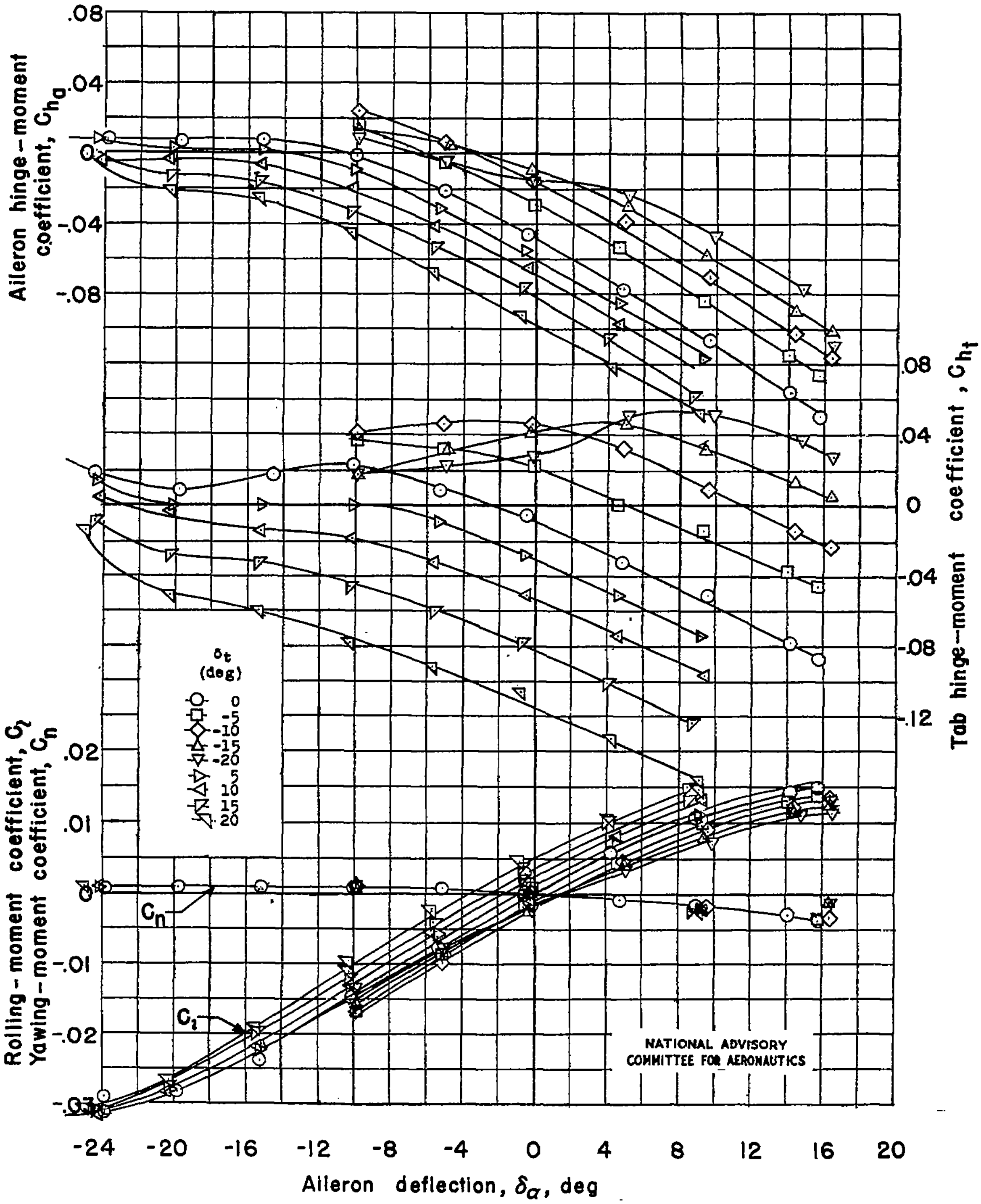


Figure 4.- Aileron characteristics of the model used for the illustrative example plotted against aileron deflection; $\alpha = 11.7^{\circ}$.

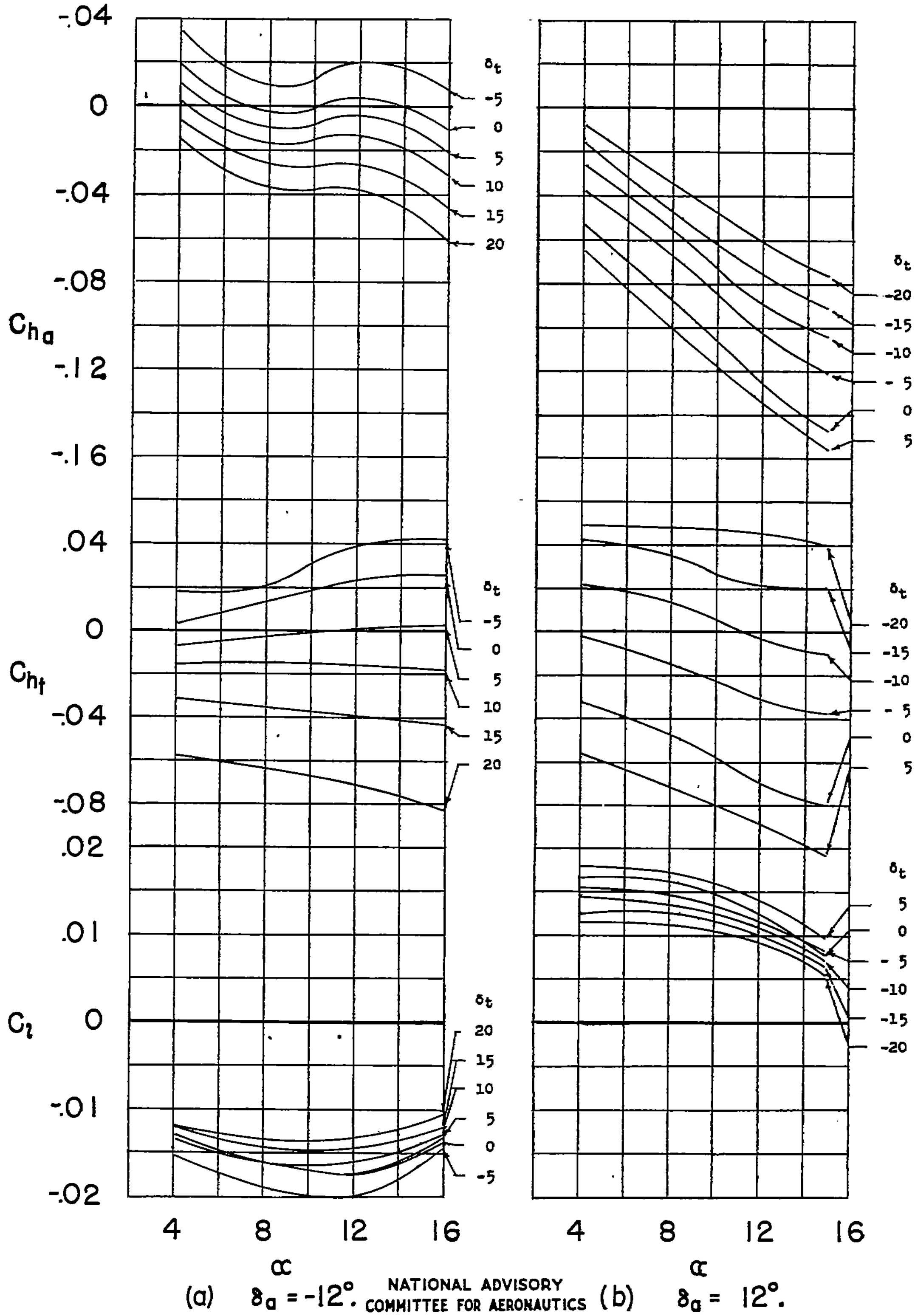


Figure 5.- Aileron characteristics of the model used for the illustrative example cross-plotted with angle of attack.

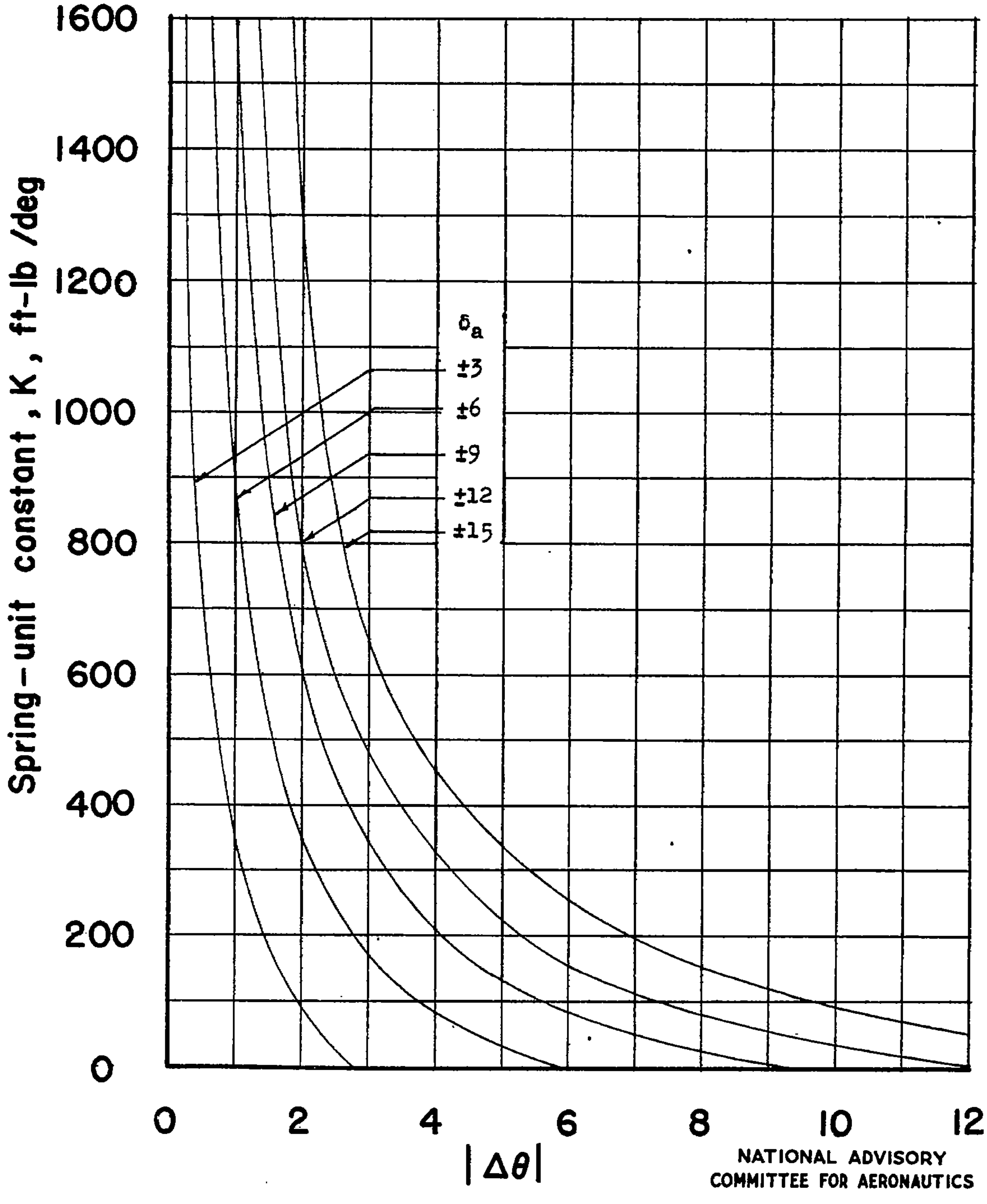


Figure 6.- The variation of the spring-unit constant required for equilibrium of the system with $\Delta\theta$ for various aileron deflections at an initial angle of attack of 14° of the model of the illustrative example.